

Three years of Fermi GBM Earth Occultation Monitoring: Observations of Hard X-ray/Soft Gamma-Ray Sources

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The Gamma ray Burst Monitor (GBM) on board Fermi Gamma-ray Space Telescope has been providing continuous data to the astronomical community since 2008 August 12. We will present the results of the analysis of the first three years of these continuous data using the Earth occultation technique to monitor a catalog of 209 sources. Although the occultation technique is in principle quite simple, in practice there are many complications including the dynamic instrument response, source confusion, and scattering in the Earth's atmosphere, which will be described. We detect 99 sources, including 40 low-mass X-ray binary/neutron star systems, 31 high-mass X-ray binary/neutron star systems, 12 black hole binaries, 12 active galaxies, 2 other sources, plus the Crab Nebula and the Sun. Nine of these sources are detected in the 100-300 keV band, including seven black-hole binaries, the active galaxy Cen A, and the Crab. The Crab and Cyg X-1 are also detected in the 300-500 keV band. GBM provides complementary data to other sky monitors below 100 keV and is the only all-sky monitor above 100 keV. In our fourth year of monitoring, we have already increased the number of transient sources detected and expect several of the weaker persistent sources to cross the detection threshold. I will briefly discuss these new sources and what to expect from our five year occultation catalog.

1. Introduction

The low energy gamma-ray/hard X-ray sky is populated largely by active X-ray binaries, active galactic nuclei, soft gamma ray repeaters, the Crab, and the Sun. The Earth occultation technique (EOT) produces flux measurements of individual source with non-imaging detectors by detecting the step-like feature in the counting rate as the source passes into or moves out of eclipse by the Earth. Here we present a results of the analysis of sources over the energy range 8 - 1000 keV utilizing EOT with the set of sodium iodide detectors aboard the Gamma-ray Burst Monitor (GBM) instrument Meegan and et al. [2009] on *Fermi*.

1.1. GBM

The Fermi Gamma-ray Burst Monitor (GBM) consists of 14 detectors: 12 NaI detectors, each 12.7 cm in diameter and 1.27 cm thick (each with effective area $\sim 123 \text{ cm}^2$ at 100 keV); and two BGO detectors, 12.7 cm in diameter and 12.7 cm thick (each with effective area $\sim 120 \text{ cm}^2$ in the 0.152 MeV range). The NaI detectors are located on the corners of the spacecraft, with different orientations in order to provide nearly uniform coverage of the unocculted sky in the energy range from 8 keV to 1 MeV. Typically 3-4 NaI detectors view an Earth occultation within 60 degrees of the detector normal vector. The two BGO detectors are located on opposite sides of the spacecraft and view a large part of the sky in the energy range ~ 150 keV to ~ 40 MeV.

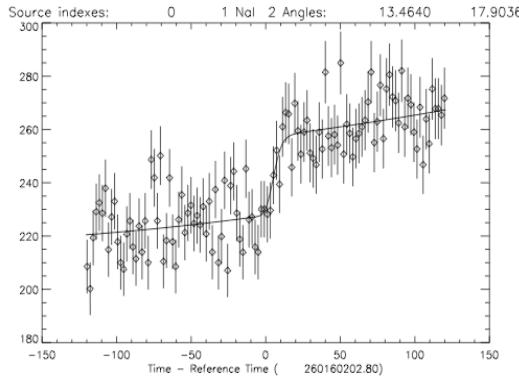


Figure 1: Example of an occultation fit window. The occultation step for the source is clearly seen at $t=0$. The best model for the fit window is shown by the solid curve.

GBM has two continuous data types: CTIME data with nominal 0.256-second time resolution and 8-channel spectral resolution and CSPEC data with nominal 4.096-second time resolution and 128-channel spectral resolution. The results presented here, with the exception of spectral analysis, use the lower-spectral resolution CTIME data for the NaI detectors.

1.2. Step Fitting Techniques

We have adapted the technique of Harmon et al. (2002) for GBM. This technique involves fitting a model consisting of a quadratic background plus source terms to a short (~ 4 min) window of data centered on the occultation time of the source of interest (See Figure 1). For GBM we have incorporated the changing detector response across the fit window into our source terms. Before any sources are fitted, good time intervals (GTIs) of GBM data are defined. The GTI intervals from the CTIME data files are shortened by 10 s to remove transient events due to GBM high voltage turn-on and turn-off. A spline model is fitted to the 12-25 keV CTIME data to eliminate large background deviations, typically on ~ 100 s time scales, due to South Atlantic Anomaly entries and exits, bright solar flares, gamma-ray bursts, and other brief bright events from the GTIs.

For each day, the occultation times for each source in the catalog are calculated using the known spacecraft positions. The time of each occultation step is taken to be the time for which the transmission of a 100 keV gamma ray through the atmospheric column is 50%. The time at which the atmospheric transmission reaches 50% is energy dependent, with lower energies absorbed at lower atmospheric densities so that a setting step will occur earlier than at higher energies.

Measuring the flux from the source of interest requires fitting a model of all sources within the fit window plus a quadratic background function to the

count rate data for each detector and each energy channel. The model includes the detector responses, assumed energy spectrum and atmospheric transmission. The fit results in a weighted scale factor for all detectors that is used to estimate fluxes;

$$F(E_{ch}) = \bar{a}(E_{ch}) * \int_{E_{ph}} f(E_{ph}) dE_{ph} \quad (1)$$

where $\bar{a}(E_{ch})$ is the weighted mean of scale factors for each detector and $f(E_{ph})$ is the flux model for each source in the fit window.

1.3. Systematic Effects

From our experience using the Earth occultation technique with BATSE and with GBM, we have identified the following systematic effects that affect Earth occultation flux measurements: (1) accuracy of the assumed source spectra, (2) large variations in the background, (3) duration of the occultation transition, (4) inaccuracies in the detector response matrices, (5) occultation limb geometry, and (6) nearby sources. In this section we describe our mitigation strategies and our efforts to reduce, account for, or quantify these effects.

By significantly deviating from the canonical spectrum for well known sources, we explored the systematic effects due to the accuracy of the source model. The detection significance was unaffected by the assumed spectra; however, the flux values were somewhat dependent on source model especially if a hard source model was used for an especially soft source or vice versa. Other sources in the fit window were not affected.

Because the background and sources are fit simultaneously, variations in the background that cannot be fitted with a quadratic function will be absorbed into the source terms and can potentially affect source measurements. Occultation steps when the spacecraft spin rate exceeds 4×10^{-3} rad s $^{-1}$ are flagged and excluded from analysis. In addition, GTIs exclude large variations in the background.

If a source is at a high latitude, the occultation will happen very slowly with respect to the window duration and step fitting becomes difficult. Steps in which the occultation exceeds 20 seconds are flagged and excluded from analysis.

The most noticeable systematic effect arises from the detector response matrices when solar panel occultations of sources. In the mass model for Fermi used to derive the responses, the solar panels are included at a fixed orientation. The true orientation of the solar panels is not fixed and can cause an unmodeled blockage of a detector. Detectors, in which any orientation of the solar panels may block the source, are excluded from the step fitting.

Every ~ 52 days, the Fermi orbit precesses so that the Earth occultation limb geometry (i.e. the projection of the Earth's limb on the sky) repeats at this period. For a particular geometry, Earth occultation flux measurements may be systematically low or high due to unmodelled sources or non-point source backgrounds such as galactic ridge emission. These systematic effects can be very difficult to identify. To mitigate these effects, we use *Swift*/Burst Alert Telescope (*Swift*/BAT) data to populate a flare database listing times and brightness levels for potentially interfering sources. The flare database along with sources identified using Earth occultation imaging Rodi and et al. [2013] are used to identify the sources used in the step fitting.

Nearby sources, especially bright or highly variable sources, can make occultation measurements very difficult. If two occultation steps occur within 8 seconds of each other, the step fitting breaks down, so we automatically flag these steps and exclude them from further analysis. Extraordinary event such as the bright outburst of A0525+26 in December 2009 will affect nearby sources such as the Crab. These effects are easily identified and we manually flag the data and exclude them from further analysis.

1.4. “Ghost” source analysis

To examine the remaining systematic effects, 3-year light curves were selected from 512 “ghost” sources run through the occultation software in conjunction with GBM imaging analyses (Rodi et al. 2011). The initial list was reduced by excluding any “ghost” sources within ± 10 degrees in longitude and latitude of the galactic center. Any “ghost” sources within 2 degrees of a source in the GBM catalog were also removed, resulting in a sample of about 200 “ghost” sources distributed over the whole sky. We investigated scatter plots of various combinations of parameters including location on the sky, flux, flux significance, flux statistical error, and flux standard deviation in all eight energy bands.

These distributions were used to estimate overall systematic errors on the flux measurements. Since no source was expected at these locations, the distribution of the flux significance in each channel is expected to be centered on zero with a standard distribution of 1.0 (See Wilson-Hodge and et al. [2012] for details). Estimates of the systematic errors derived from this analysis are shown in Table I.

1.5. Sensitivity

Calculating the sensitivity for the Earth occultation technique is made challenging by the constantly changing spacecraft source geometry, detector response, and the constantly changing hard X-ray sky.

Table I Systematic error estimates for GBM Earth occultation analysis

Energy band (keV)	Systematic error (mCrab)
8-12	3.4
12-25	2.8
25-50	2.2
50-100	1.5
100-300	3.1
300-500	3.4

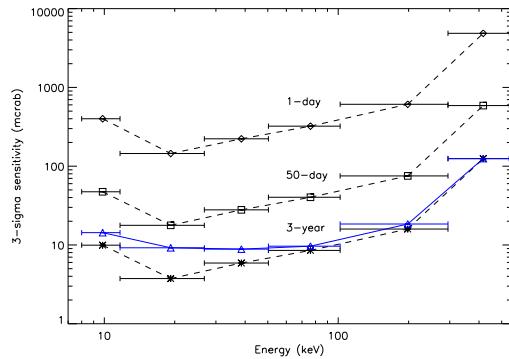


Figure 2: Estimated 3σ sensitivities for the GBM Earth occultation technique from 8-500 keV. Statistical estimates are shown for 1-day (diamonds), 50-day (squares), and 3-year (asterisks) intervals. Systematic errors from Table 1 have been added in quadrature to the 3-year statistical errors and are plotted as triangles connected with solid lines.

To estimate the statistical sensitivity of the technique, we used four detected sources, the Crab (a galactic source in a relatively uncrowded region), Centaurus A (an active galaxy at high galactic latitude and high declination to account for steps lost when the source was at high beta angles), NGC 4151 (another active galaxy at high galactic latitude and moderate declination), and GRS 1915+105 (a persistent black hole system near but not at the galactic center). For each of these sources, 1-day, 50-day, and 3-year average measured fluxes and statistical errors were computed. The average error in each energy channel for each source was then computed. The approximate statistical sensitivity for each source was computed as three times the average error in mCrab units. For the three year averages only the systematic errors from Table I were added in quadrature. Figure 2 shows the estimated sensitivities, averaged for the four sources.

1.6. Comparisons

As a final check we compared our occultation results in the energy range from 12-50 keV to *Swift*/BAT 15-50 keV survey results for eight sources using 2-4

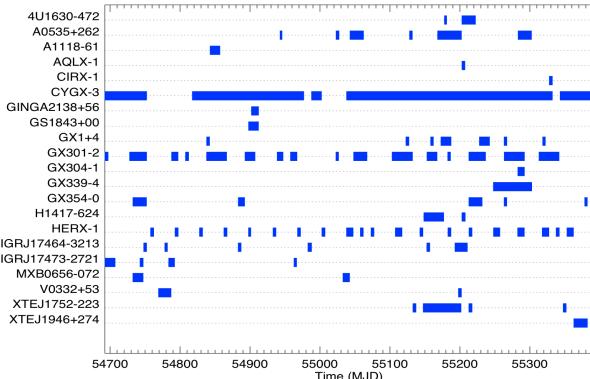


Figure 3: A sample of transients detected by the Earth occultation method. The solid bars indicate the times in which the transient was detected at the 5σ level.

day averages. We obtained very close agreement with the exception of Sco X-1. The excess in Sco X-1 was expected due to the particularly soft spectrum and the lower energy band used for GBM occultation analysis.

2. Results

In August 2012 we published our 3 year catalog Wilson-Hodge and et al. [2012] that included 209 sources. 99 sources were detected at 5σ (Category A) including 40 LMXB/NS, 31 HMXB/NS, 12 BHC, 12 AGN, and the Crab Nebula. We also had several sources detected between 3.5 and 5σ (Category B). We continue to add sources to our catalog, currently 219 sources, and additional transients are being detected regularly (See Figure 3).

2.1. Sources above 100 keV

One of EOT's special abilities is to monitor sources above 100 keV. We regularly detect 4 black hole candidates (BHC); Cygnus X-1, 1E 1740-29, GRS 1915+105, and Swift J1753.5-0127, the Seyfert 2 galaxy Cen A and the Crab Nebula above 100 keV. We have also detected flares in the BHCs XTE J1752-223 and GX 339-4 above 100 keV.

2.1.1. Crab Nebula

The Crab Nebula is detected regularly up to 300 keV in our monitoring program. Since 2008 August, a $\sim 7.0\%$ (70 mCrab) decline has been observed in the overall Crab Nebula flux in the 15-50 keV band Wilson-Hodge and et al. [2011]. This decline was independently confirmed in the 15-50 keV band with *Swift/BAT*, the *Rossi X-ray Timing Explorer* Proportional Counter Array (*RXTE/PCA*), and the Imager

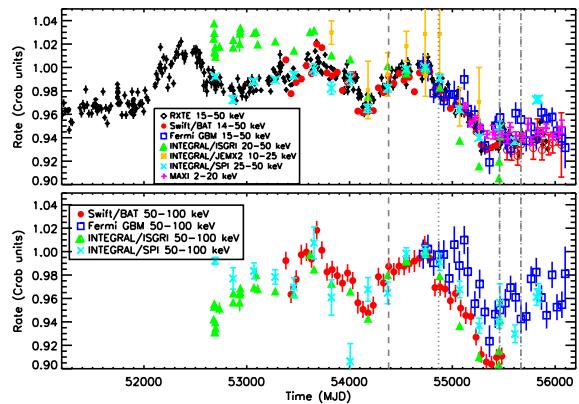


Figure 4: Top - A light curve of the Crab Nebula from 15-50 keV from *Fermi*/GBM (blue squares), RXTE (black diamonds), *Swift*/BAT (red filled circles), INTEGRAL/ISGRI, INTEGRAL/JEMX2, INTEGRAL/SPI, (green triangles, yellow squares, blue X's respectively) and MAXI 2-20 keV (purple pluses). Rates are normalized to *Fermi*/GBM measurements in 2008 August. Bottom - A similar light curve of the Crab Nebula from 50-100 keV from *Fermi*/GBM (blue squares), RXTE (black diamonds), *Swift*/BAT (red filled circles), INTEGRAL/ISGRI (green triangles), and INTEGRAL/SPI (blue X's).

on-Board the *INTEGRAL* Satellite (IBIS) (See Figure 4). This was the first conformation of the X-ray variability of the Crab Nebula.

The EOT is also capable of spectral analysis by binning the sky into instrument response bins in space-craft coordinates. By using CSPEC data we customize our energy channels to best match the source of interest. Figure 5 shows an average 69 energy spectra from the Crab utilizing 14,629 occultation steps for an exposure time of approximately 1.7Ms (assuming 120s of exposure per step). The spectrum was fit with a broken power-law model and the best fit parameters were $\Gamma_1 = 2.057 \pm 0.009$, $\Gamma_2 = 2.36 \pm 0.05$ with the break at 98 ± 9 keV and a $\chi^2 = 1280.44$ with 963 degrees of freedom ($\chi^2_{\nu} = 1.33$). This result is consistent with Jourdain and Roques [2009] who fit *INTEGRAL*/SPI Crab data.

Extrapolating the Crab spectrum obtained from GBM EOT to GeV energies obtained from the *Fermi*/LAT 2FGL catalog suggests that the power-law is an adequate description of the data through GeV energies (See Figure 6).

2.1.2. Cygnus X-1

The BHC Cygnus X-1 is regularly observed with EOT to 300 keV especially during it's hard/low state. GBM's EOT has routinely identified state changes in this black hole candidate Wilson-Hodge and Case [2010]. Figure 7 shows light curves for Cygnus X-1 from 12 - 500 keV where the state changes and flares are readily seen up to 300 keV.

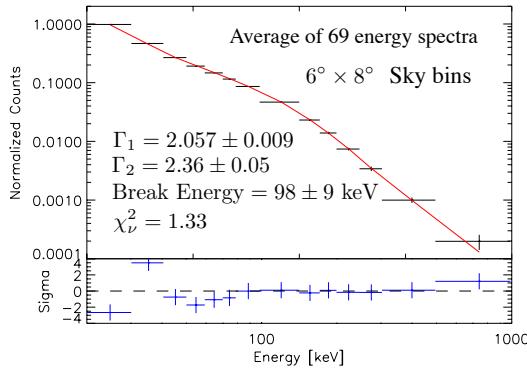


Figure 5: Points are the average of 69 spectra for the Crab while the red curve is the best fit model.

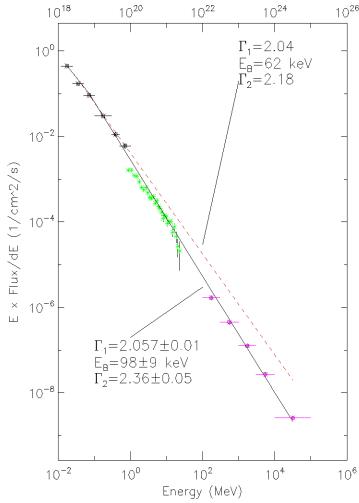


Figure 6: The black points are the average of 69 spectra obtained by the EOT. The green points are data obtained from COMPTEL, while the pink points are the data from the *Fermi*/LAT 2FGL catalog. The solid curve is the extrapolation of the best fit spectrum from the EOT while the dashed line is the extrapolation of the spectrum obtained by Jourdain and Roques [2009].

2.1.3. XTE J1752-223

The transient BHC XTE J1752-223 was discovered by RXTE Markwardt and et al. [2009] on 2009 October 23. Fermi/GBM, using the EOT, observed XTE J1752-223 from October 23, 2009 (MJD 55127) to January 20, 2010 (MJD 55216) Wilson-Hodge and et al. [2009] while the source was in a spectrally hard state. The EOT stopped detecting the source when the source shifted from a spectrally hard to soft state Curran and et al. [2011]. Fermi/GBM again detected the source between April 1, 2010 (MJD 55287) to April 13, 2010 (MJD 55299) when the source again transitioned to a hard state before its emission fell back to quiescence. Figure 8 shows the light curves, from the GBM occultation project, in five energy bands (8-12

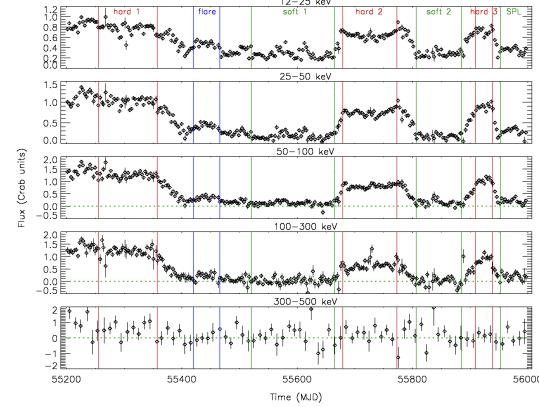


Figure 7: The EOT measured fluxes for Cygnus X-1 shown for 12-25, 25-50, 50-100, 100-300, 300-500 keV energy bands. The vertical colored lines indicate times of state changes.

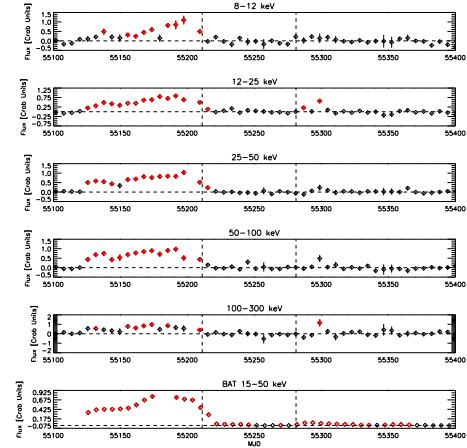


Figure 8: Light curves of XTE J1752-223, from the GBM occultation project, in five energy bands (8-12 keV, 12-25 keV, 25-50 keV, 50-100 keV, and 100-300 keV). The figure also shows the Swift/BAT 15-50 keV survey data for the same period. Red points denote 3 σ detections or better. The vertical dashed lines indicate state changes from hard to soft and again from soft to hard.

keV, 12-25 keV, 25-50 keV, 50-100 keV, and 100-300 keV). The figure also shows the Swift/BAT 15-50 keV survey data for the same period.

2.1.4. GX 339-4

The BHC GX 339-4 is characterized by rapid time variability and low/hard X-ray states similar to Cygnus X-1. The flux observed by GBM began to increase starting in early 2010 January Case and et al. [2011] and continued to increase up to a level of ~ 400 mCrab (1225 keV), ~ 650 mCrab (2550 keV), ~ 800 mCrab (50100 keV), and ~ 550 mCrab (100300 keV) by early 2010 April, after which it began to rapidly decrease. It returned to quiescence in the higher energy bands by mid-April and in the 1250 keV band by the end of April. Figure 9 shows the light curves, from the

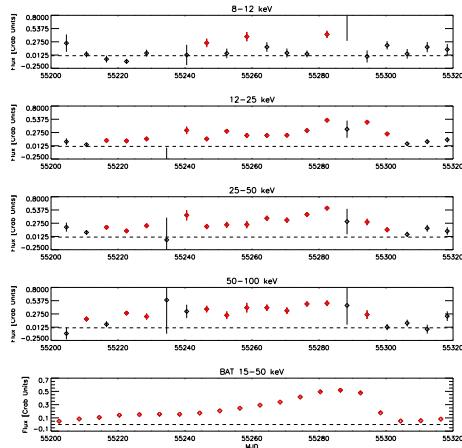


Figure 9: Light curves of GX 339-4 from the GBM occultation project, in four energy bands (8-12 keV, 12-25 keV, 25-50 keV and 50-100 keV) integrated over 6 days. The bottom panel shows the Swift/BAT 15-50 keV survey data for the same period. Red points denote 3σ detections or better. The vertical dashed lines indicate state changes from hard to soft and again from soft to hard.

GBM occultation project, in four energy bands (8-12 keV, 12-25 keV, 25-50 keV and 50-100 keV). The figure also shows the Swift/BAT 15-50 keV survey data for the same period.

2.2. Additional Results - A 0535+26

GBM EOT continues to provide valuable information on BHCs and on other sources such as Be X-ray binaries as well as active galaxies in the energies between 8-1000 keV. Monitoring sources for outbursts and state changes provides valuable information to the X-ray and gamma-ray community.

A 0535+26 is a Be X-ray binary that exhibits transient outbursts occasionally associated with periastron passage. Generally two types of outbursts are observed, smaller ones that peak at a few hundred mCrabs and giant outbursts that may peak at several Crab. As we learn more about these outbursts, it becomes more difficult to separate the two classifications Camero-Arranz and et al. [2012]. In 2010 April an intermediate outburst ~ 1 Crab was observed (See Figure 10).

3. Conclusion

GBM EOT currently provides online light curves and data for 218 sources. We are currently automati-

¹<http://heastro.phys.lsu.edu/gbm/>

ing our spectral capabilities and will soon have spec-

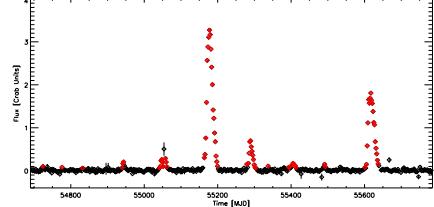


Figure 10: Two day average fluxes for A0535+26, from the GBM occultation project in the energy from 12-100 keV. The four normal outbursts prior to the giant outburst in 2009 are detected as well as the following three normal outburst as well as the second giant outburst in 2012. The red points are 5σ detections or better

tra available on our webpage¹. New sources are constantly being added to our monitoring program and we expect to significantly increase the number of sources detected in our next catalog. In addition, we expect to roll out new data products that promise to improve the versatility of the analysis currently available. In sum, the EOT project is a dynamic project that keeps improving and expanding to the needs of the scientific community.

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